

Recent BSM Highlights from ATLAS and CMS

Vector-like-Quarks/Leptoquarks/New vector bosons

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University



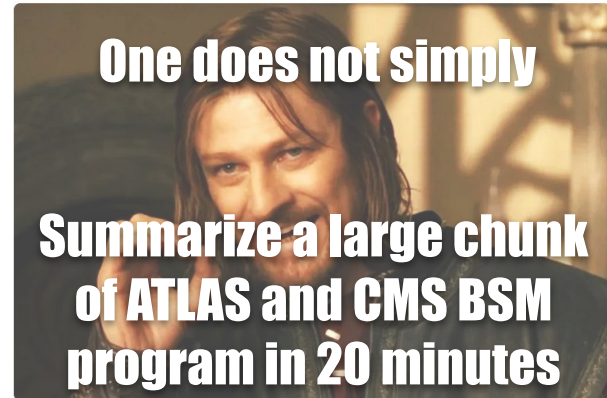
What to expect today

Both ATLAS and CMS have an extensive BSM program. More than 50 searches in 2023/2024 that could fit within this talk scope !

Today I'll try to :

- Give you a brief snapshot of the experimental status at the LHC of three specific areas of BSM physics that we are looking into:
 - Vector-like-quark, **Leptoquarks** and 'generic' **W'/Z' searches**
- Describe few recent analyses (6 of them) in those areas with some detail
 - All of them with run 2 data (139 fb^{-1} at $\sqrt{s}=13 \text{ TeV}$)

There are heavy recency and personal bias in my choices of analyses to describe but decisions had to be made. I didn't want to just give you a list of results in rapid fire! If you want to discuss specific analyses that I didn't cover on these areas please talk to me during the conference !



Sean Bean in Lord of the Rings (Credit: New Line)

Vector-like-quarks (VLQ) The one-slide version

“Quarks”: Colored, fractionally charged, spin 1/2 particles

“Vector-like”: Left and right chiralities have the same weak isospin



A chiral 4th generation has strong constraints from Higgs measurements and EW precision data but VLQ can have bare mass terms, loosening those constraints

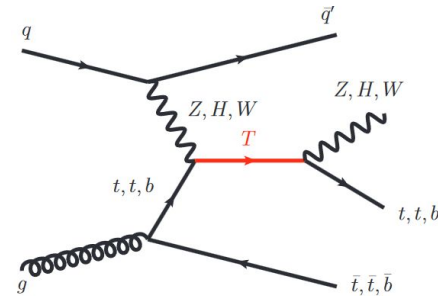
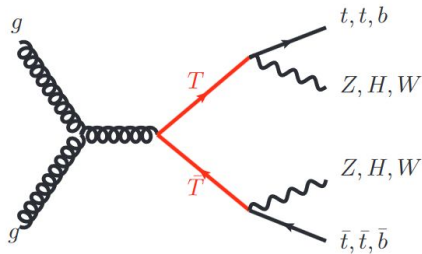
Can help canceling the divergent top correction to the Higgs boson without fine tuning (Hierarchy problem)

Q[e]	VLQs					
	singlets		doublets		triplets	
5/3			$\begin{pmatrix} X \\ T \end{pmatrix}$		$\begin{pmatrix} X \\ T \end{pmatrix}$	
2/3	(T)		$\begin{pmatrix} T \\ B \end{pmatrix}$		$\begin{pmatrix} T \\ B \end{pmatrix}$	$\begin{pmatrix} T \\ B \\ Y \end{pmatrix}$
-1/3		(B)		$\begin{pmatrix} B \\ Y \end{pmatrix}$		
-4/3						

Couple with SM quarks and appear in Little/Composite Higgs models, GUTS, Topcolor among others

How do we look for VLQ at the LHC?

In many models, VLQ couple preferentially to third generation, and can decay through many different channels, involving W,Z or H boson. Wealth of final states generally involving tops and b's, but with lots of options for the boson decays



Pair production:

- Dominant for light VLQ ($< 1\text{TeV}$)
- More 'model independent' (QCD production)
- Historically more explored

Single production:

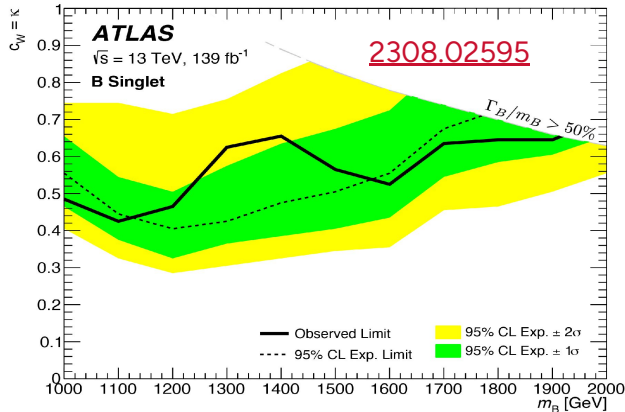
- Can be dominant for high masses
- Depends on mass and coupling
- More complicated signal modelling

The story so far

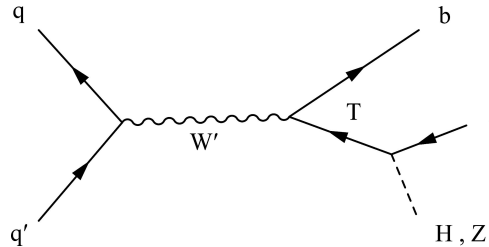
ATLAS: 8 full Run 2 analyses
 CMS: 7 full Run 2 analyses

Full list in backup

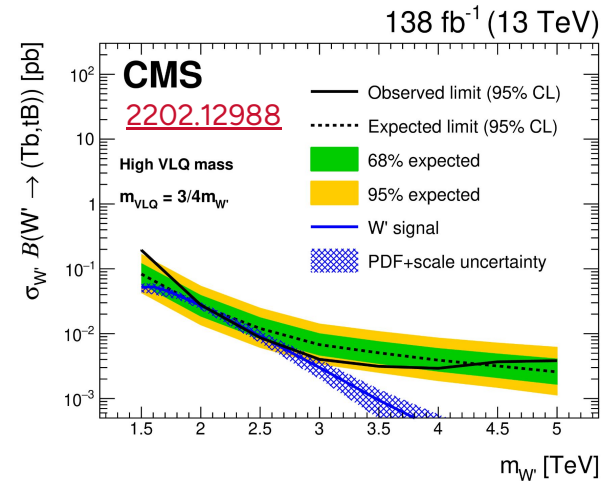
Huge effort by both collaborations on covering all of the possible final states and both single and pair production analyses! Mainly focused on 3rd generation couplings and interpretations based on minimal models. Good coverage of final states with mass limits between 1.5 and 2 TeV, considering a wide range of couplings/widths.



CMS: Has considered models with BSM couplings (W', Z' decaying into VLQ)



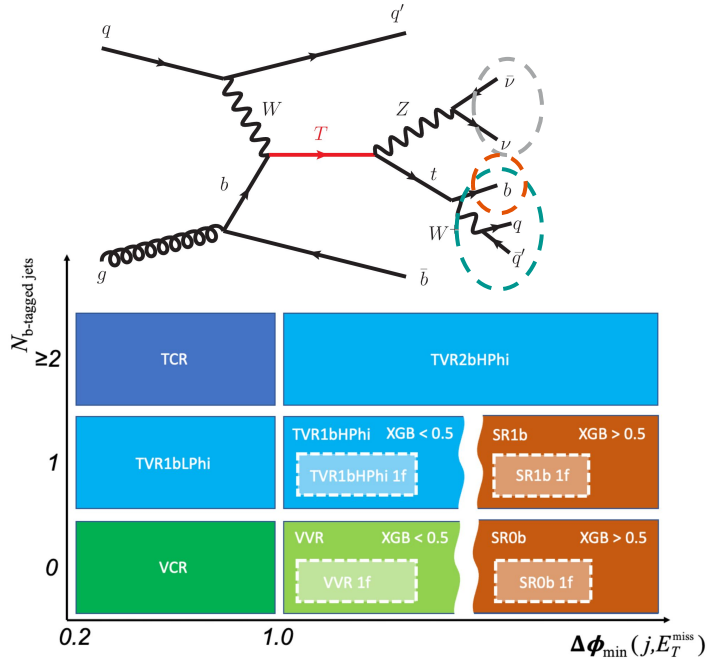
ATLAS: Generally considering larger widths, more coupling/mass coverage. Up to 50% in many recent searches



Just a small selection of the many results from the last year..

ATLAS Monotop search [2402.16561](#)

Search on single-top final states with interpretations in DM and VLQ production



Selection

- One **top-tagged large-R jet** ($p_T > 350$ GeV)
- additional **b-tagged jets**
- missing transverse energy (> 250 GeV)

XGBoost (XGB): Boosted Decision Tree (BDT)

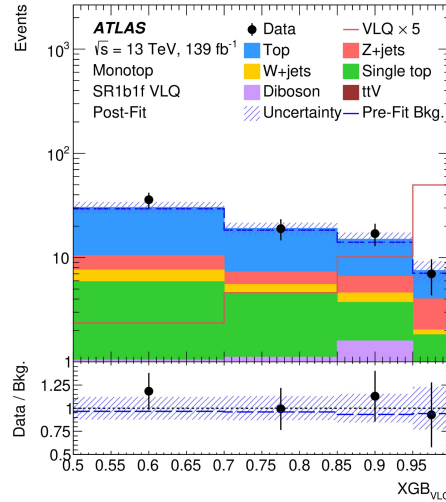
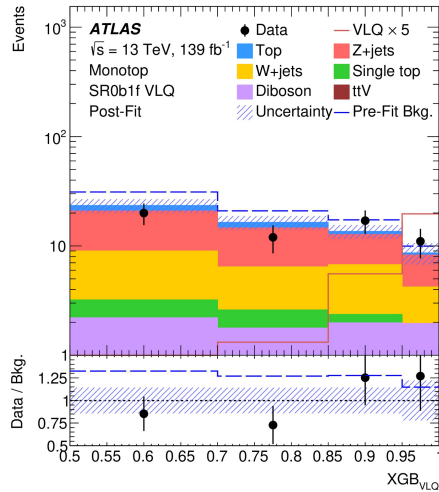
- To separate signal and background (tt and Z+jets dominant)
- 13 variables as input -> MET and b-jet higher importance

Top-tagging: technique used to identify large-R jets coming from top-quarks: **Deep Neural network (DNN) using substructure information**

B-tagging: technique used to identify jets originated from b-quarks: **DNN using tracking and vertexing information**

ATLAS Monotop search

[2402.16561](#)

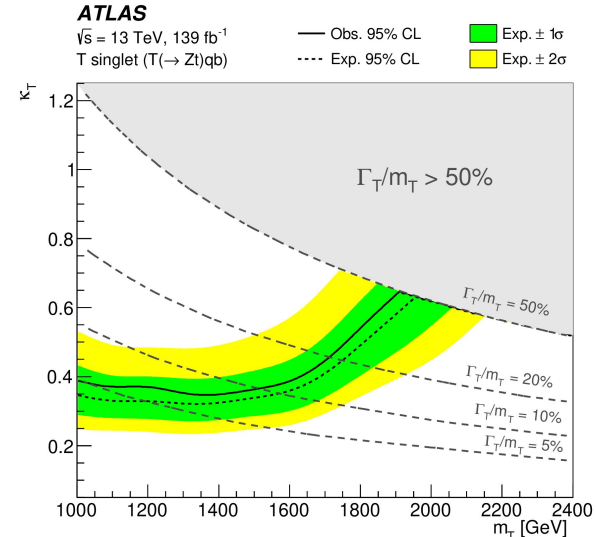


Interpreted in the context of a **singlet T VLQ** with different values of the coupling.
Mass limit improved ~ 400 GeV with respect to previous results !

Simultaneous fit in signal all SR and CR

- **XGB score** in SR, Event yields in CR
- All templates are MC based

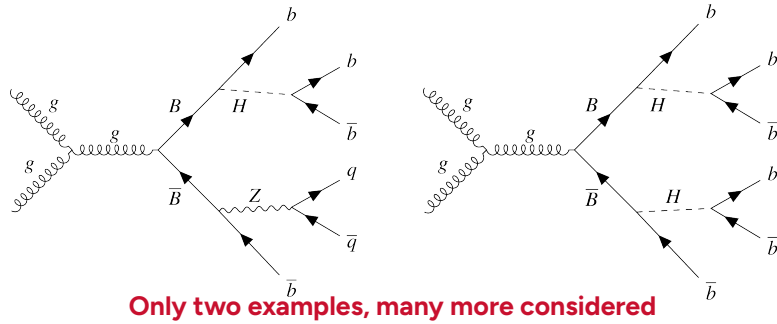
Good agreement with the SM prediction



Bottom VLQ CMS search

2402.13808
pair production

Many different decay modes under the same roof, Considering $B \rightarrow Hb$, $B \rightarrow Zb$ and $B \rightarrow Wt$. Fully hadronic decays for all combinations except $Z \rightarrow l^+l^-$ which is also considered



Categories with **large number of jets** and a large amount of H_T (> 1350 GeV)

Jet multiplicity	Leptonic category	Fully hadronic category
3	bHbZ, bZbZ	—
4	bHbZ, bZbZ	bHbH, bHbZ, bZbZ
5	—	bHbH, bHbZ, bZbZ, bHtW, bZtW
6	—	bHbH, bHbZ, bZbZ, bHtW, bZtW

B-tagging is used to define the signal regions and to reconstruct the H and Z candidates

- Resolved (with two b-tagged jets)
- merged (with one bb tagged large-R jet)
- **Leptonic category is the exception**

B candidates reconstructed using a χ^2 method to select the right combination of jets to use.

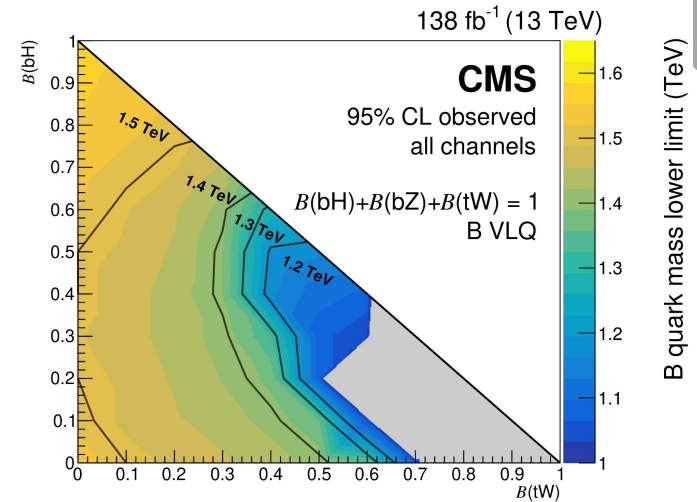
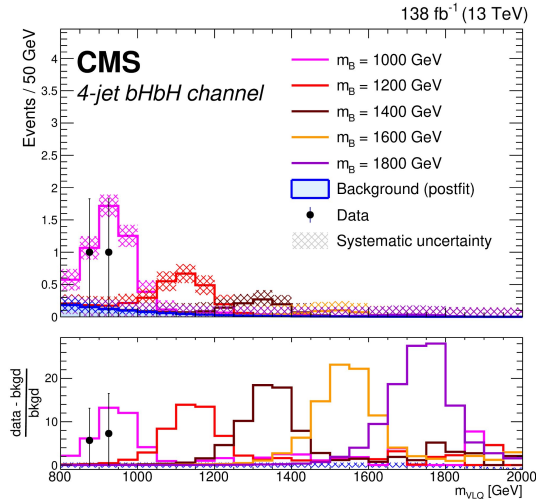
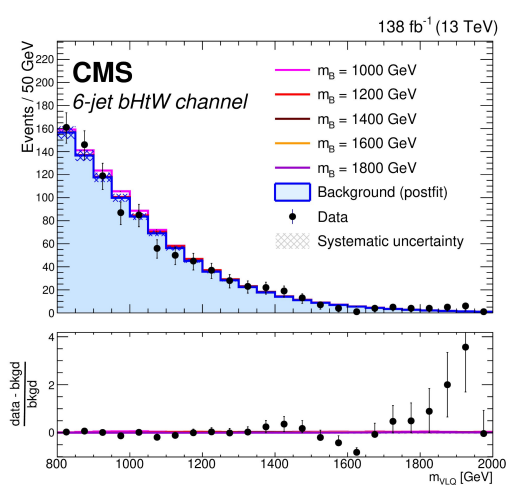
$$\chi_{\text{mod}}^2 = \frac{(\Delta m_{\text{VLQ}} - \overline{\Delta m_{\text{VLQ}}})^2}{\sigma_{\Delta m_{\text{VLQ}}}^2} + \frac{(m_1 - \overline{m_1})^2}{\sigma_{m_1}^2} + \frac{(m_2 - \overline{m_2})^2}{\sigma_{m_2}^2},$$

Bottom VLQ CMS search

2402.13808
pair production

A fully data-driven approach is used to estimate the background in each category.

- Template fit in the pre-selection regions (before b-tagging requirements)
- Normalization correction from a low M_{VLQ} region

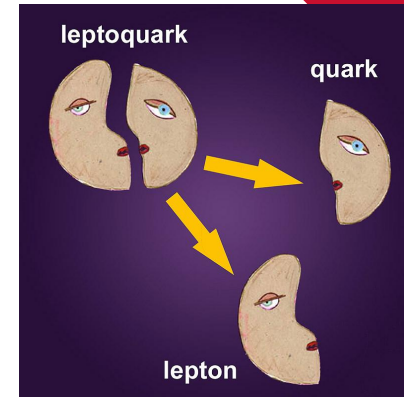


No statistically significant excess is found in any of the regions after fitting M_{VLQ} , and limits are set for different values of the branching ratios.

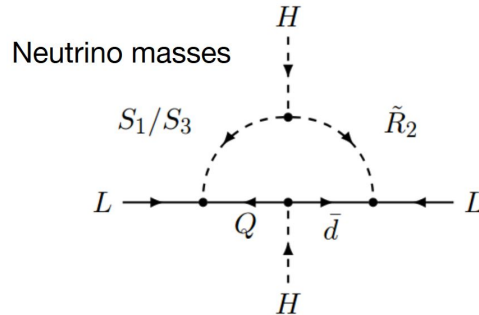
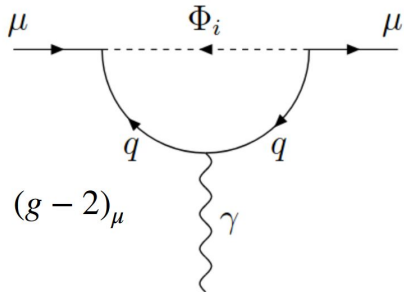
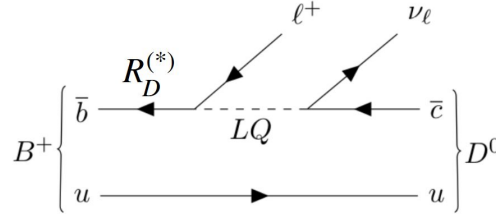
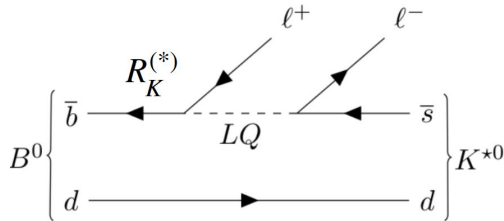
Leptoquarks (LQ)

The one-slide version

Scalar or vector particles that carry **color, charge, baryon and lepton numbers**. By allowing direct couplings between lepton and quarks, they are useful to explain many SM problems !



From fermilab today / October 2009



Two types of LQ in models

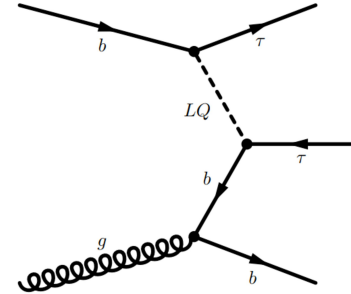
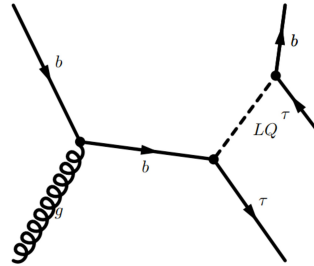
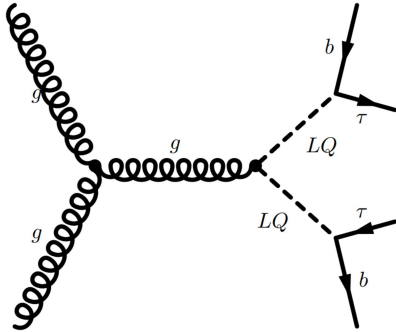
- $LQ_{1,2,3}$: Mix with only one generation
- LQ_{mix} : Allow for **cross-generation**



Lepton Flavor Universality violation (LFUV) scenarios !

How do we look for LQ

Similar situation of VLQs Both pair and single production scenarios are possible. Most papers focused on LQ^3 , with final states containing τ , ν , b-quarks and top-quarks



Pair production:

- Dominant for light LQ ($<1\text{TeV}$)
- More 'model independent' (QCD production)
- Historically more explored

Single production:

- Can be dominant for high masses
- Depends on mass and coupling
- More complicated signal modelling

Note that both 'up-type' LQ ($Q=2/3$) and 'down type' LQ ($Q=-1/3$) are possible and they lead to different final states

The story so far

ATLAS: 14 full run 2 analyses
 CMS: 8 full run 2 analyses

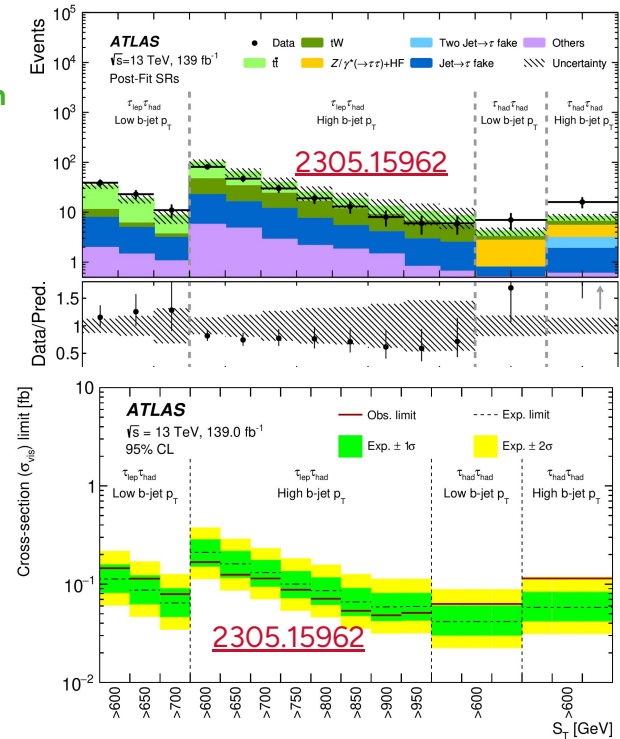
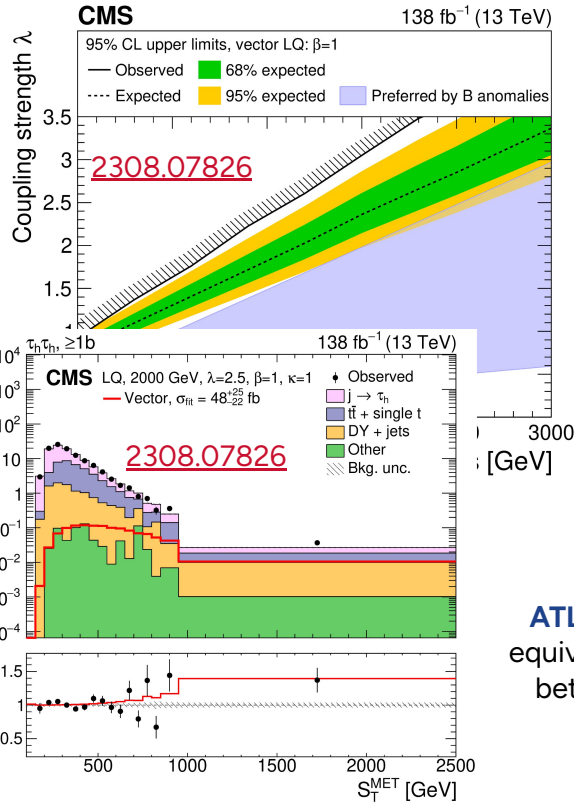
Full list in backup

Number of papers exploded synchronously with the interest in flavor anomalies, initial focus on 3rd generation LQ and pair production but a fair amount of papers allowing for cross-generational couplings are also available

Masses up to 1.8 TeV excluded from pair production. Some interesting recent results on single production analyses

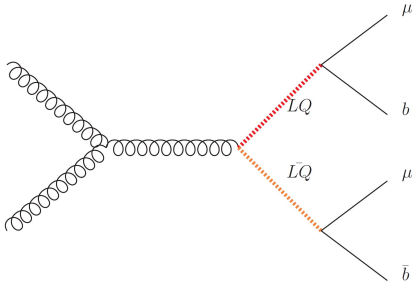
CMS: Small excess for a 3rd generation vector LQ in a $b\tau$ decay. Dominated by events in 'low' sensitivity region and not present in 'high' sensitivity ones

ATLAS: Hints of similar behavior in the equivalent ATLAS search. However, much better compatible with SM prediction



CMS Pair production search $L\bar{L}Q \rightarrow \mu b \mu \bar{b}$

2402.08668



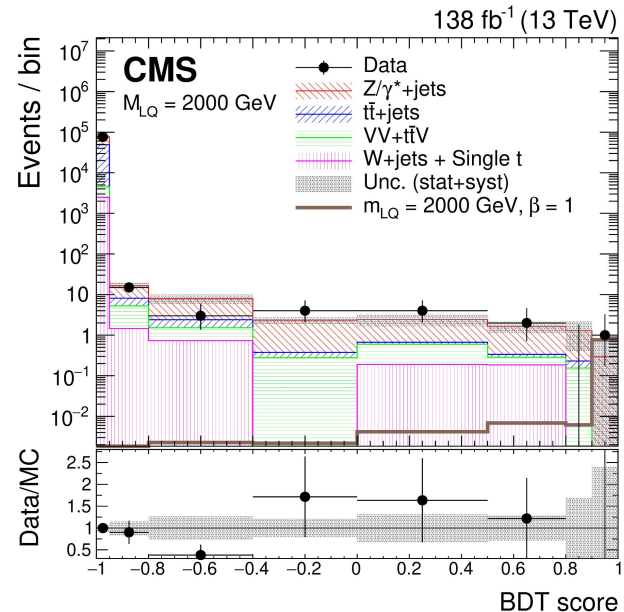
Straightforward preselection

- Exactly two isolated and well separated muons ($p_T > 35$ GeV)
- two jets ($p_T > 50$ GeV) with at least one of them b-tagged.
- Additional requirements on $m_{\mu\mu}$ and $S_T^{\mu\mu j}$ (Scalar p_T sum)

BDTs are trained at preselection level (One per signal hypothesis). **Eleven variables** are used as input to the BDT

One-bin signal regions defined using the BDT

- Score cut chosen to optimize discovery potential.
- Background estimated using MC simulation
- Normalization corrected using two dedicated CR
 - **Z+jets/tt+jets** and **VV/ttV**
 - Built using dedicated $m_{\mu\mu}$ selections

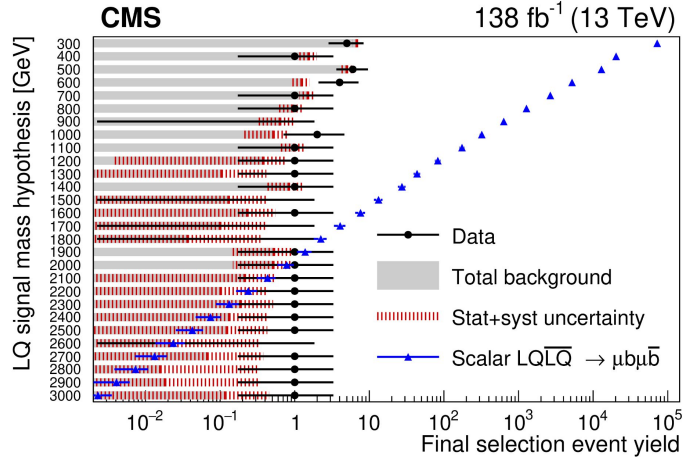


CMS Pair production search

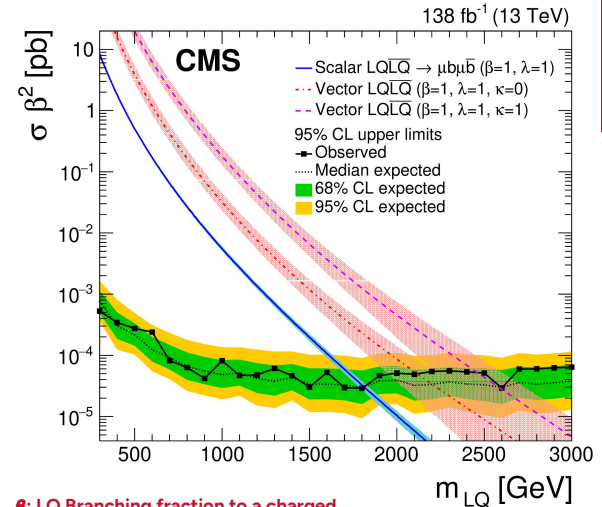
LQLQ $\rightarrow \mu b \mu \bar{b}$

2402.08668

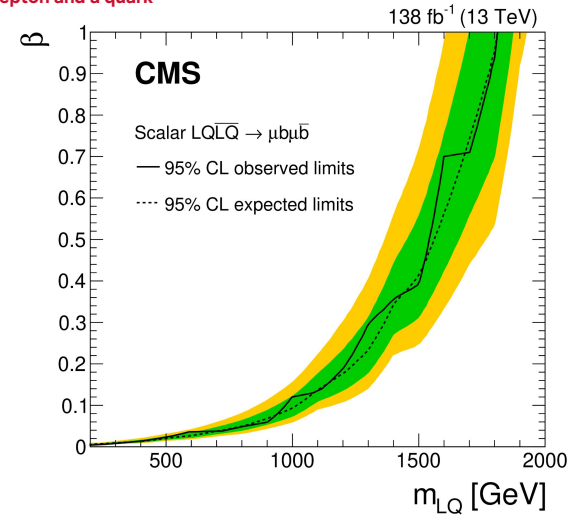
Background expected yields and data compared in the different regions for each signal mass hypothesis.



Limits obtained for both scalar and vector LQ, with mass limit depending on the model. Exclude $m_{LQ} < 2$ TeV for any minimal coupling model with $\beta = 1$ which is the strongest limit to date



β : LQ Branching fraction to a charged lepton and a quark



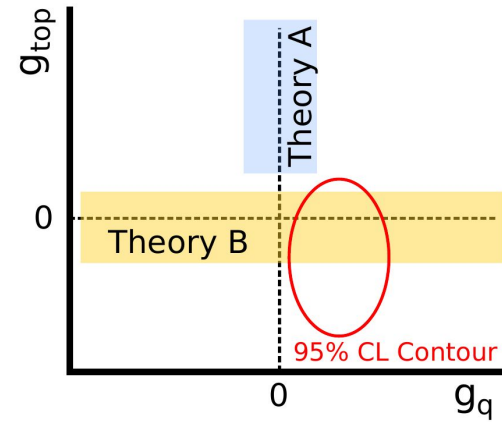
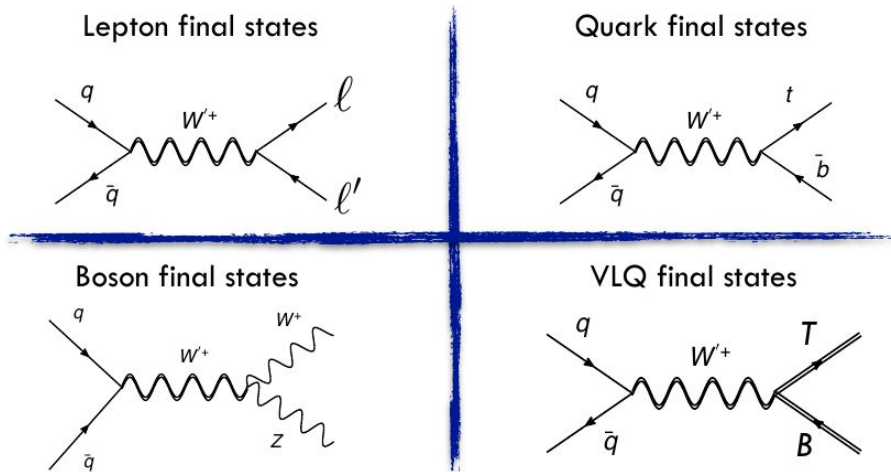
An aside on combinations

Two of the analyses I have yet to talk about are combinations of several analysis. What do I mean by combination?

Statistical combination of **several analyses with a common underlying model** or production mechanism

Realistic models have a varied phenomenology

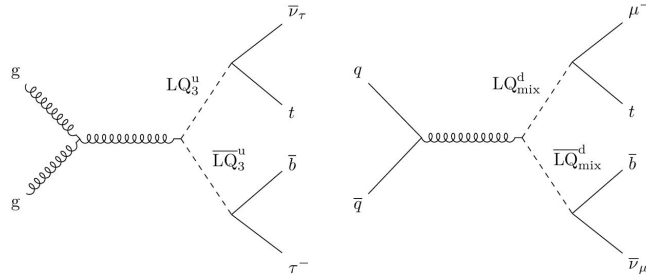
- Access to discovery via **small compatible excesses**
- Additional axes in N-dimensional parameter space



ATLAS Leptoquark combination

2401.11928

pair production with b-jets

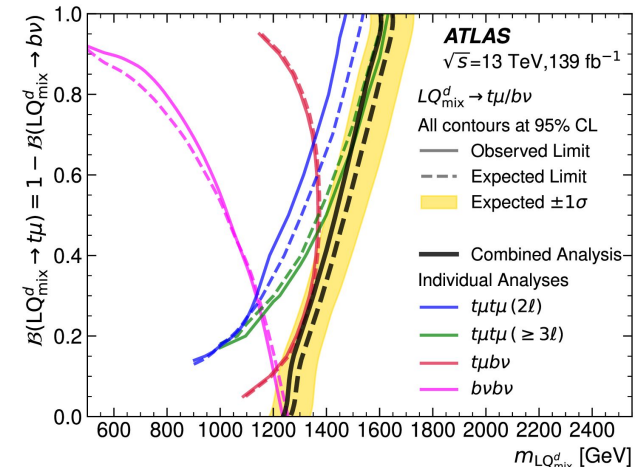
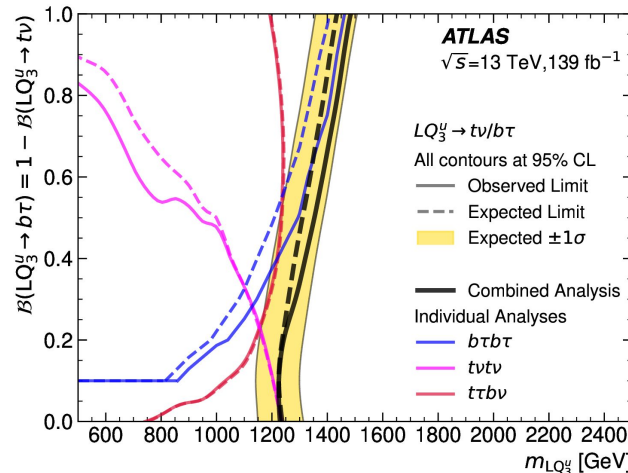


$tvb\tau$
 $b\tau b\tau$
 $t\tau t\tau$
 $tvtv$
 $bvbv$

$blbl$
 $tltl (2l)$
 $tltl (> 3l)$
 $tvbl$

All relevant SR and CR are used in a combined likelihood fit

Only some examples, All possible decays of the leptoquarks into quarks of the third generation and charged or neutral leptons of any generation investigated. Full set of limits in backup



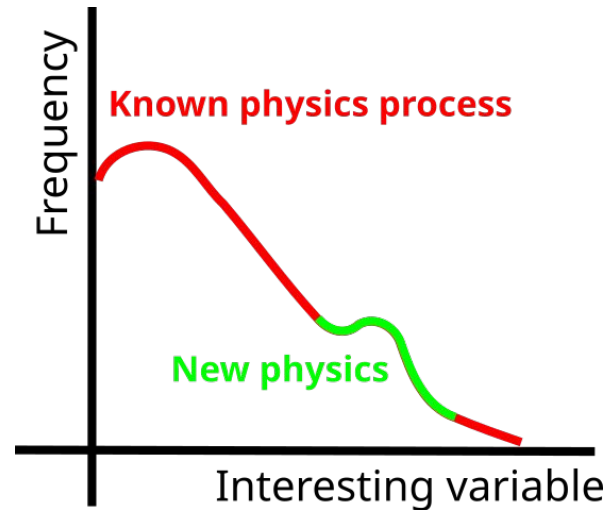
New vector bosons

Large category of models that predict new W'/Z' bosons with different properties. Sometimes they appear as DM mediators and sometimes they couple strongly to specific generations (3rd for example), among many other possibilities

Both collaborations have looked for W' and Z' in **many different final states** and are exploring new ones with some regularity

Typical benchmark models for general searches
Sequential Standard Model (SSM) or Heavy Vector Triplet (HVT)

Often searches in the invariant mass of the expected decay (dijet, tt , bb , tb , e^+e^- , etc...). Very good coverage at high mass, Low mass still has uncovered phase-space !



ATLAS Spin 1 resonance combination

[2402.10607](#)

18 different searches combined in a single framework ! Interpreted in the context of HVT, using the multidimensional coupling space to different fermions/bosons to obtain contours in several 2D planes

Most analyses are orthogonal by construction, but some additional requirements were implemented to ensure it when necessary

Bosonic decays

Leptonic decays

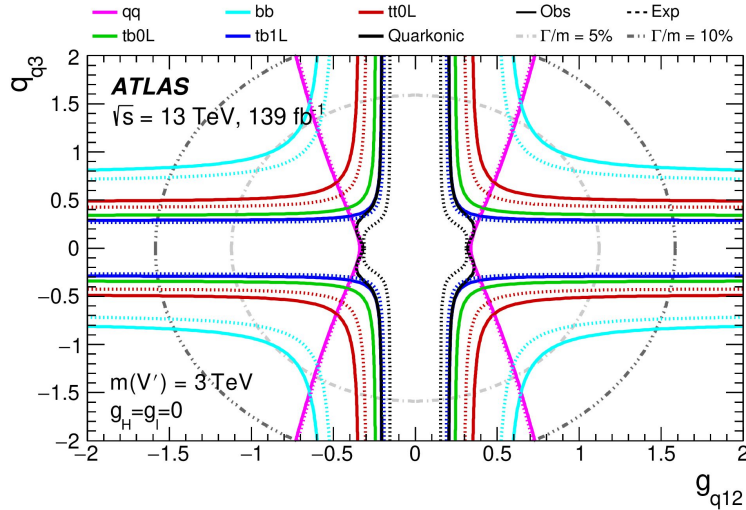
Quarks decays

Analysis	Leptons	E_T^{miss}	Jets	b -tags	Top-tags	VBF
$WW/WZ \rightarrow qqqq$	0	Veto	$\geq 2J$	-	-	-
$WW/WZ \rightarrow \ell\nu qq$	1e, 1 μ	Yes	$\geq 2j, \geq 1J$	0, 1, 2	-	Yes
$WZ \rightarrow qq\nu\nu$	0	Yes	$\geq 1J$	0	-	Yes
$WZ \rightarrow qq\ell\ell$	2e, 2 μ	-	$\geq 2j, \geq 1J$	0	-	Yes
$WZ \rightarrow \ell\nu\ell\ell$	3 \subset (e, μ)	Yes	-	0	-	Yes
$WH/ZH \rightarrow qqbb$	0	Veto	$\geq 2J$	1, 2	-	-
$ZH \rightarrow \nu\nu bb$	0	Yes	$\geq 2j, \geq 1J$	1, 2	-	-
$WH \rightarrow \ell\nu bb$	1e, 1 μ	Yes	$\geq 2j, \geq 1J$	1, 2	-	-
$ZH \rightarrow \ell\ell bb$	2e, 2 μ	Veto	$\geq 2j, \geq 1J$	1, 2	-	-
$\ell\nu$	1e, 1 μ	Yes	-	-	-	-
$\tau\nu$	1 τ	Yes	-	-	-	-
$\ell\ell$	$\geq 2e, \geq 2\mu$	-	-	-	-	-
$\tau\tau$	0, 1e, 1 μ	Yes	-	0, ≥ 1	-	-
tt0L	0	-	2J	1, 2	2	-
tb0L	0	-	$\geq (1j+1J)$	≥ 1	1	-
tb1L	1e, 1 μ	Yes	2j, 3j	1, 2	-	-
qq	0	-	2j	0	-	-
bb	0	-	2j	1, 2	-	-

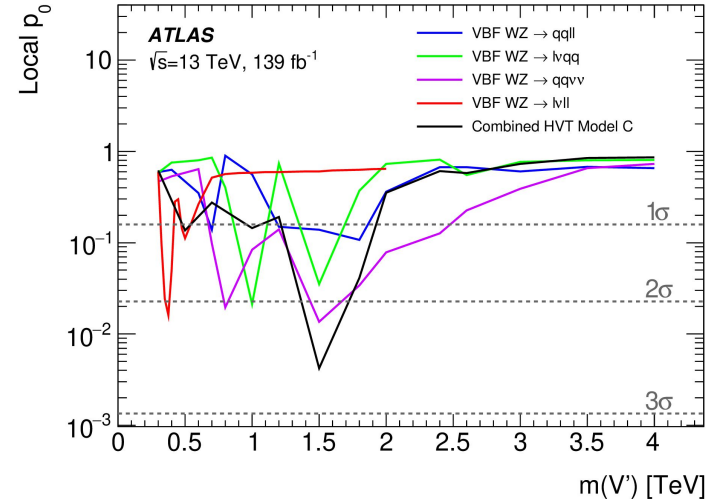
ATLAS Spin 1 resonance combination

2402.10607

Couplings to quarks, lepton and the Higgs boson (possible to also separate the third generation quark coupling) used to build several 2D planes. Also interpreted for few interesting HVT benchmarks (Specific coupling values)



Only one example, more can be found in backup.
 Improvement with respect to individual channels
 across the board

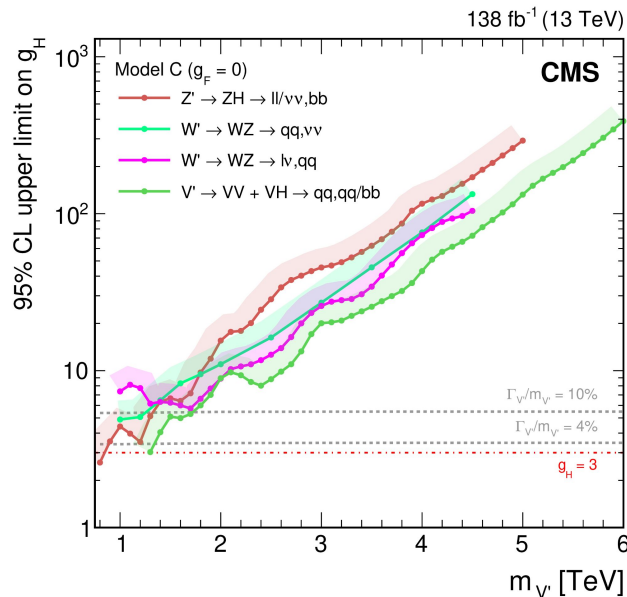
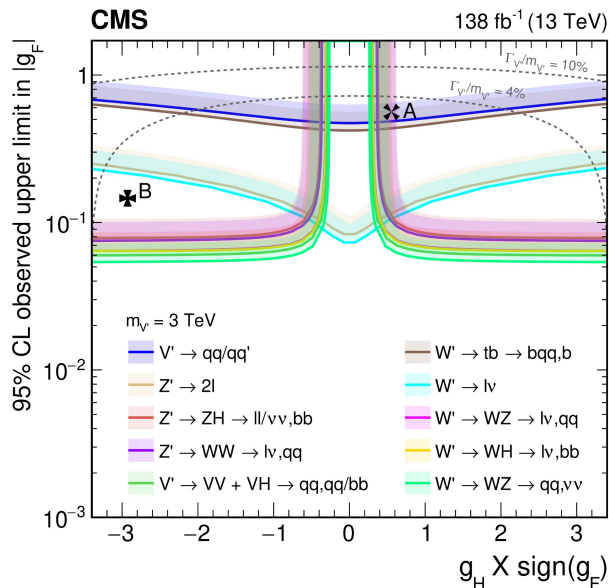


Combination of small excesses around 1.5 for VBF searches increased significance when combined. HVT model C corresponds to $g_H = 1.0$ and $g_f = 0.0$. No fermion couplings!

CMS review on resonances decaying to hX

2403.16926

Not a full statistical combination, but a comparison of previous searches using a common interpretation within the HVT model space (Among other interpretations).



Similar multidimensional approach as the ATLAS combination! Shows clearly that model C phase-space (VBF dominated) is mostly unconstrained by LHC data

Summary

- Described the overall status of three of the more active BSM areas in ATLAS and CMS
 - Vector-like-quark, **Leptoquarks** and 'generic' **W'/Z' searches**
- Showed some recent highlights in those areas
 - **ATLAS: Monotop search (VLQ interpretation only)** [2402.16561](#) Submitted to JHEP
 - **ATLAS Leptoquark combination** [2401.11928](#) Submitted to Phys. Lett. B
 - **ATLAS Spin 1 resonance combination** [2402.10607](#) JHEP 04 (2024) 118
 - **CMS: Pair production VLB search** [2402.13808](#) Submitted Phys. Rev. D
 - **CMS: Pair production LQLQ $\rightarrow\mu b\mu b$ search** [2402.08668](#) Accepted Phys. Rev. D
 - **CMS: Review on hV and VV resonances** [2403.16926](#)
- ... And flashed glimpses of few more
 - Even then, I've only covered a small piece of the BSM program
- **Lots of analyses performed during Run 2, with sadly, no hints of new physics**
 - Many ideas being explored to extract as much as possible from the ongoing Run 3 in both collaborations and leave **no stone unturned** !

THANK YOU FOR YOUR ATTENTION





BACKUP

The full list of VLQ analyses

Full Run 2 only

ATLAS

- [2402.16561](#) □ Monotop (Single production)
- [2401.17165](#) □ Pair production $Wb + X$
- [2308.02595](#) □ $B \rightarrow bH(bb)$
- [2307.07584](#) □ Single production opposite sign multilepton
- [2305.03401](#) □ Single production $Ht/Zt + X$ (1 lepton channel)
- [2212.05263](#) □ Pair production $T \rightarrow Zt$ (1 lepton + MET)
- [2210.15413](#) □ Pair production opposite sign multilepton
- [2201.07045](#) □ Single production all-hadronic

CMS

- [2402.13808](#) □ Pair production B to dileptonic/hadronic
- [2302.12802](#) □ Single production $T \rightarrow tH(\gamma\gamma)$
- [2209.07327](#) □ Pair production (leptonic)
- [2202.12988](#) □ $W' \rightarrow Tb/Bt$ (all-hadronic)
- [2201.02227](#) □ Single production $T \rightarrow Zt$ (jets + MET)
- [2008.09835](#) □ Pair production BB (all-hadronic)
- [2405.05071](#) □ Single production $T \rightarrow Ht/Zt$ (all-hadronic)

The full list of LQ analyses

Full Run 2 only

ATLAS

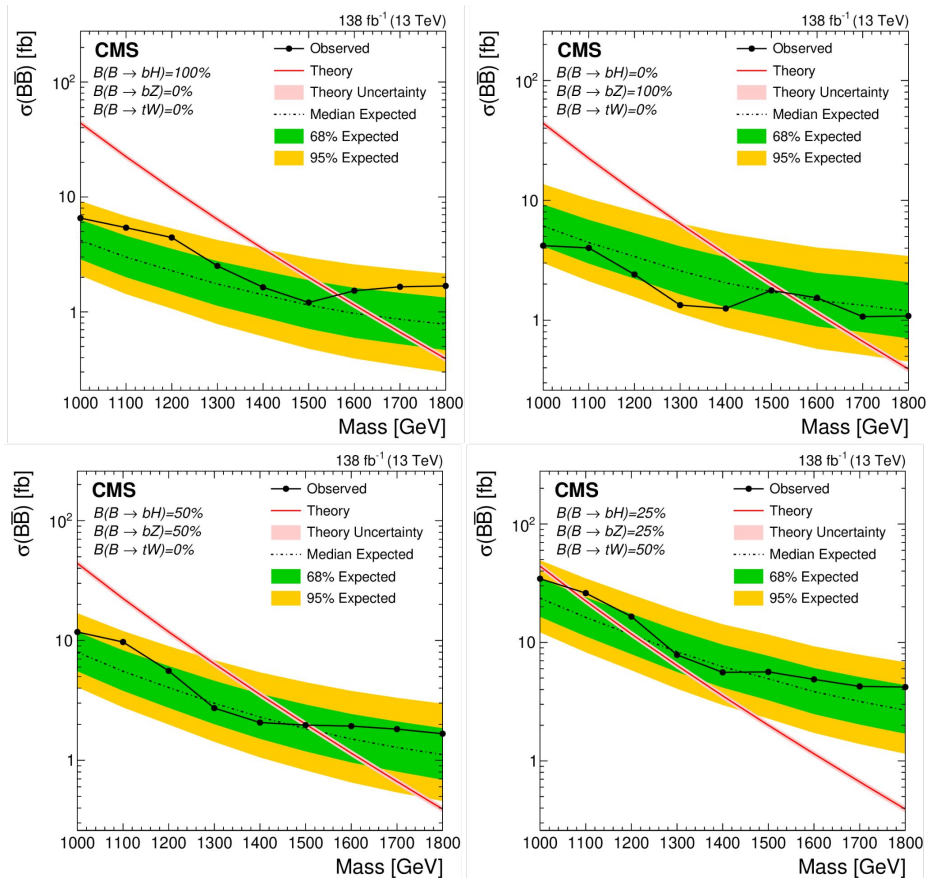
- [2403.06742](#) □ LFV in top production/decay
- [2401.11928](#) □ Pair production (b-jets combination)
- [2306.17642](#) □ Pair production ($t\bar{t}\ell\bar{\ell}$ multilepton)
- [2305.15962](#) □ Single production ($b\tau\tau$)
- [2303.09444](#) □ Single production ($\tau\tau$ + jets)
- [2303.01294](#) □ Pair production ($b\tau b\tau$)
- [2210.04517](#) □ Pair production (t/b + ℓ final states)
- [2108.07665](#) □ Pair production (all τ final states)
- [2101.12527](#) □ Pair production (bb+MET)
- [2101.11582](#) □ Pair production ($t\tau t\tau$)
- [2010.02098](#) □ Pair production ($t\bar{t}\ell\bar{\ell}$ hadronic tops)
- [2006.05872](#) □ Pair production first and second gen.
- [2004.14060](#) □ Pair production (t/b + MET)

CMS

- [2402.08668](#) □ Pair production (muons and bottom quarks)
- [2308.07826](#) □ Third generation LQ \rightarrow τb (all modes)
- [2308.06143](#) □ Single production LQ _{τb} (tau initiated production)
- [2212.12604](#) □ Non-resonant LQ (τ + MET)
- [2208.02717](#) □ Non-resonant LQ ($\tau\tau$ final state)
- [2202.08676](#) □ Third generation (Multilepton inclusive search)
- [2107.13021](#) □ Single LQ first generation (MET + jets)
- [2012.04178](#) □ Single and pair third generation (t/b+ $\tau\nu$ final states)

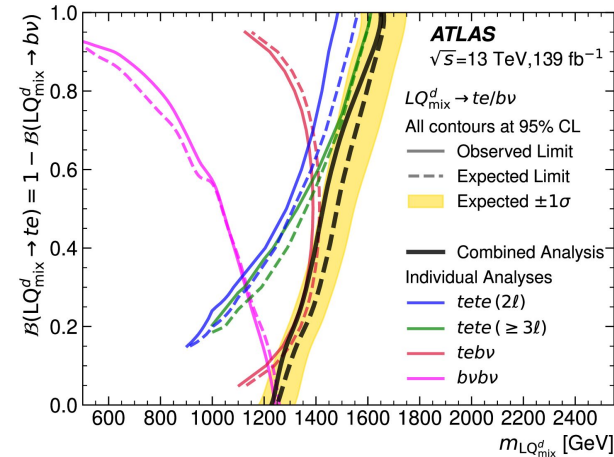
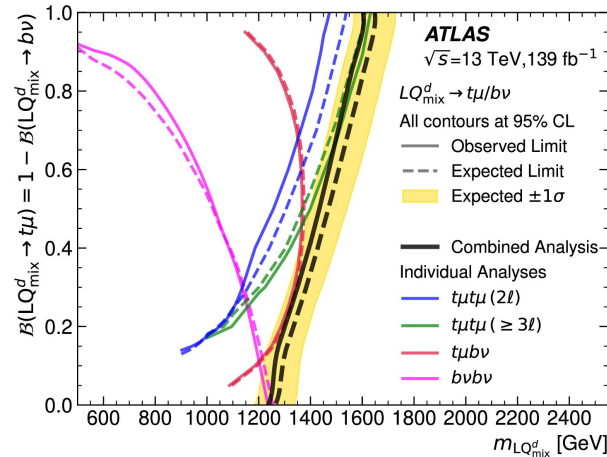
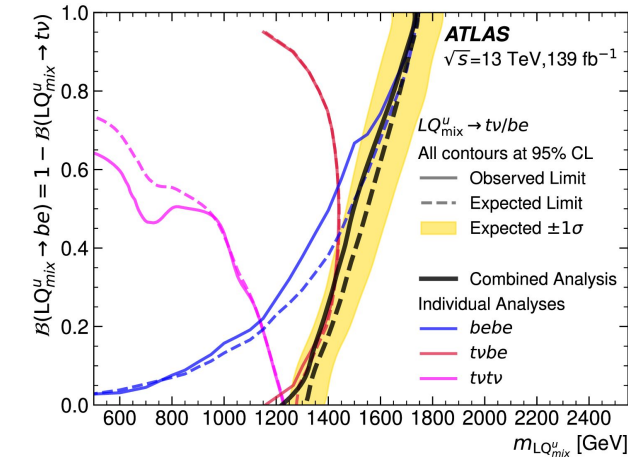
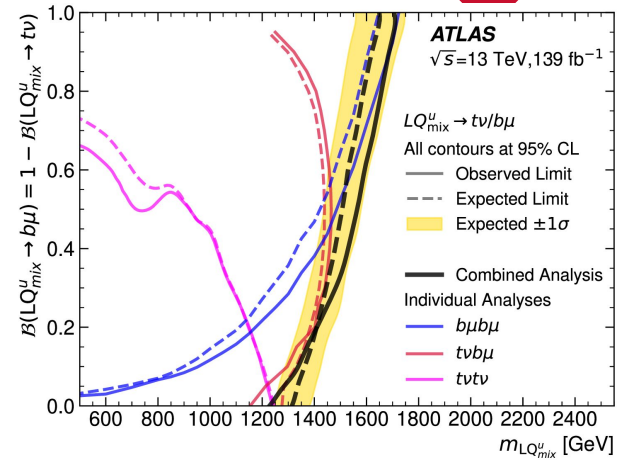
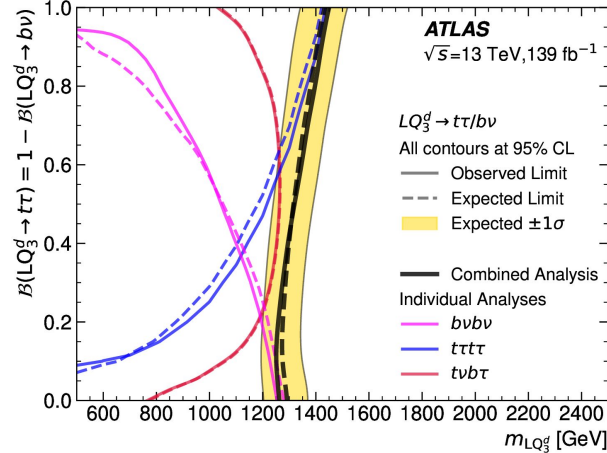
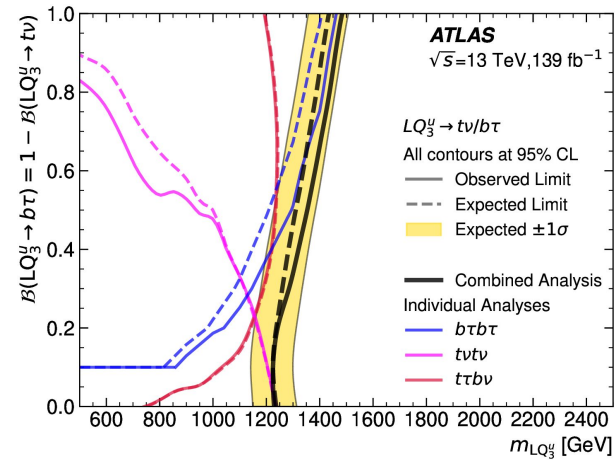
More VLQ limits from CMS

2402.13808



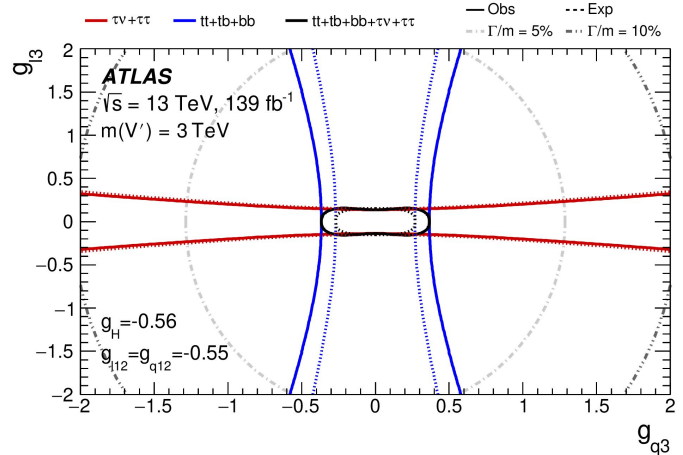
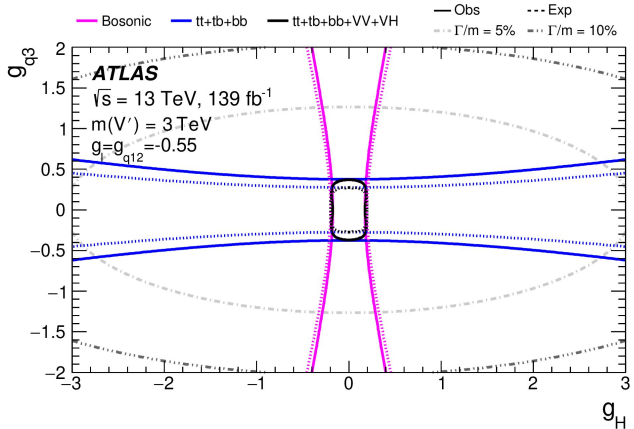
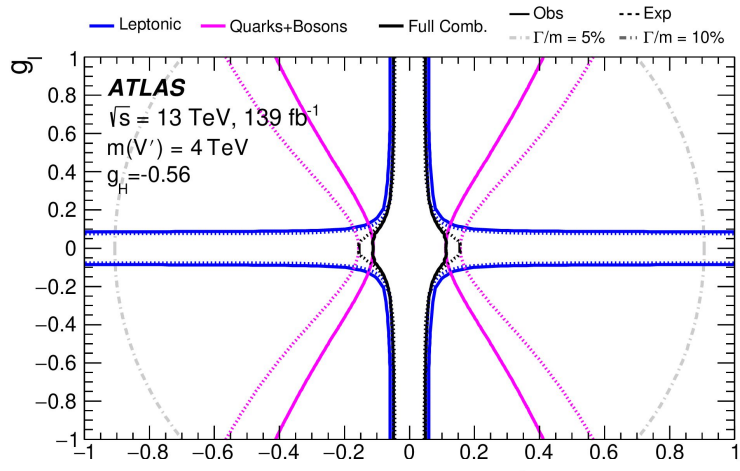
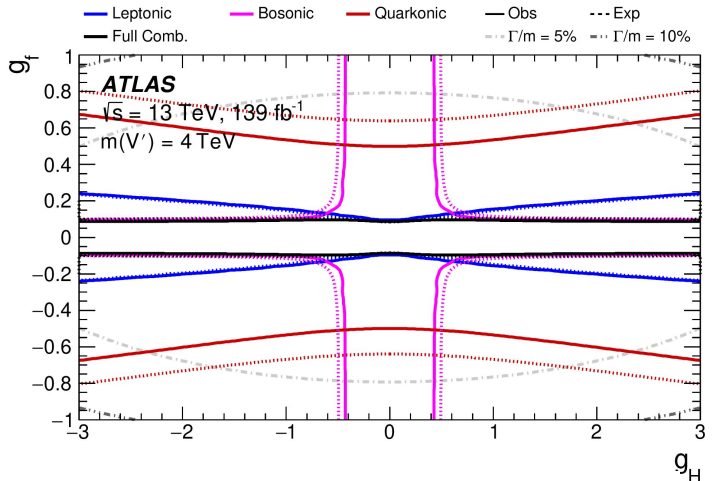
ATLAS Leptoquark combination

2401.11928



ATLAS Spin 1 resonance combination

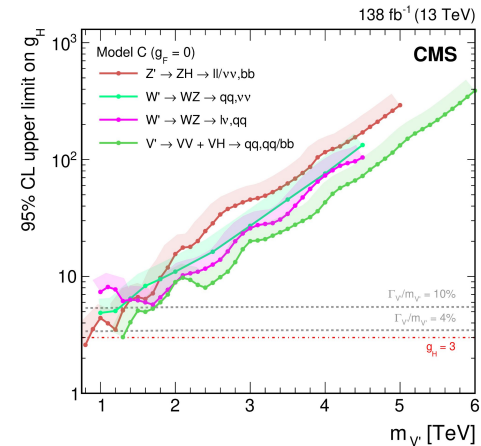
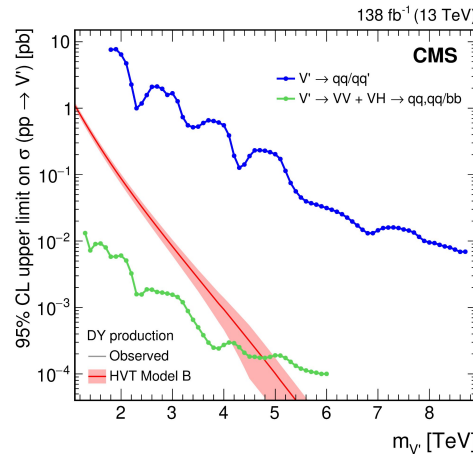
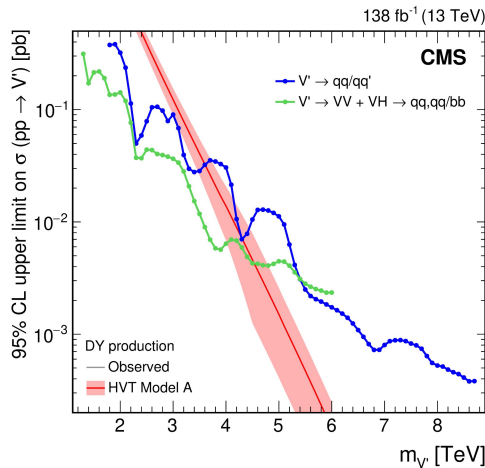
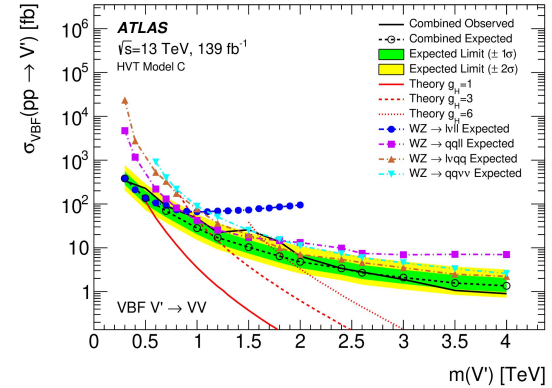
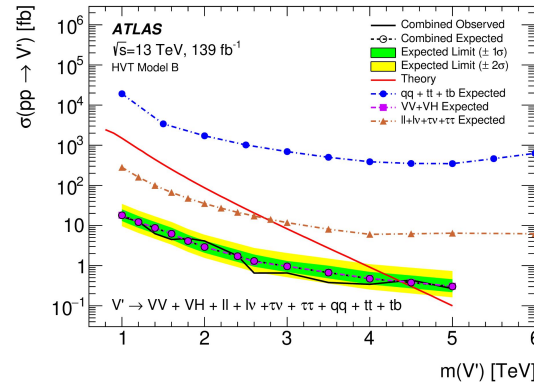
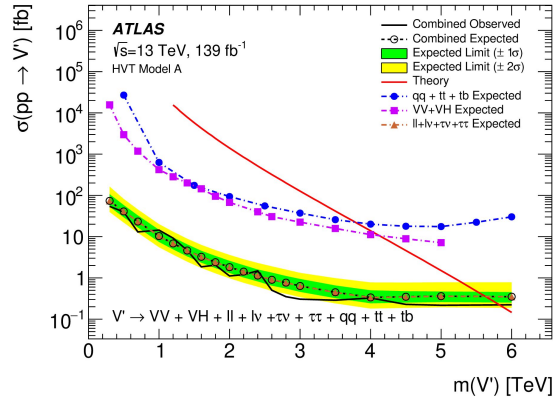
2402.10607



HVT result comparisons

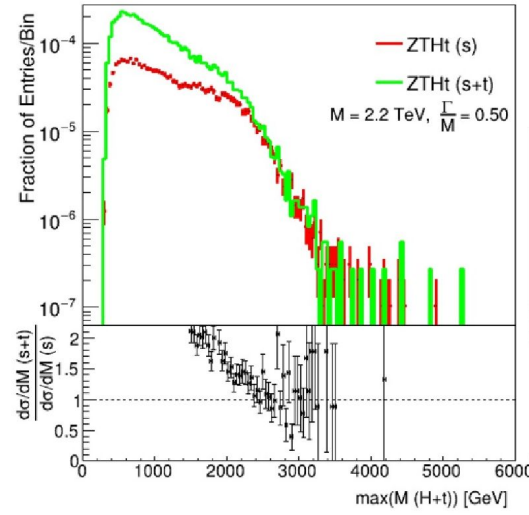
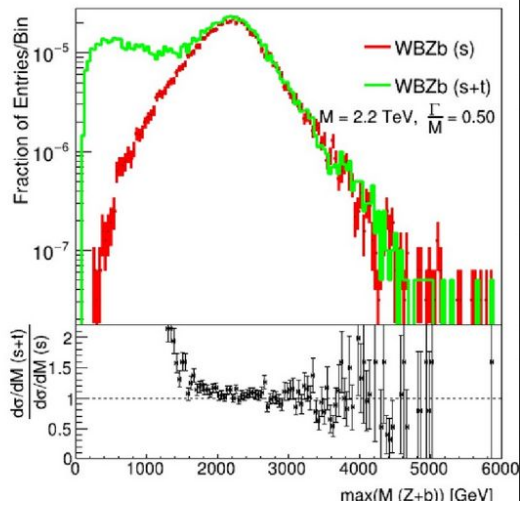
2402.10607

2403.16926



Single VLQ modelling

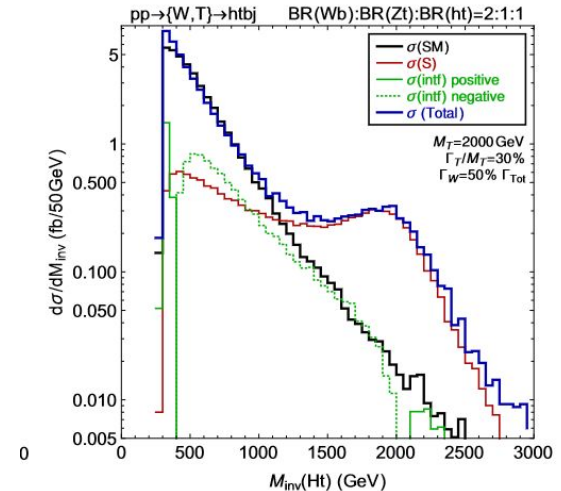
[2202.02640](#) Roy, Avik and Andeen, Timothy



Interference with the standard model can be important in certain productions modes and shape effects need to be taken into account

Non resonant production contributions very large for several production modes when considering large widths/couplings !

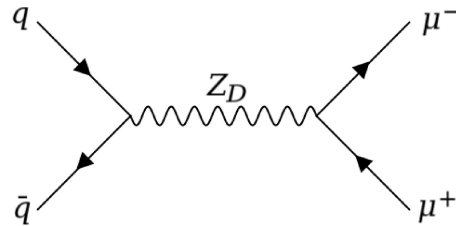
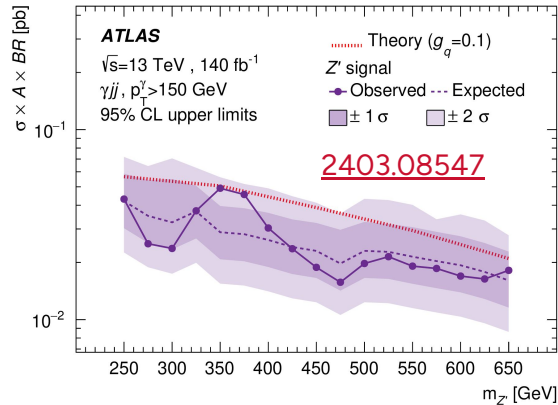
[2105.08745](#) Deandrea, Aldo et al



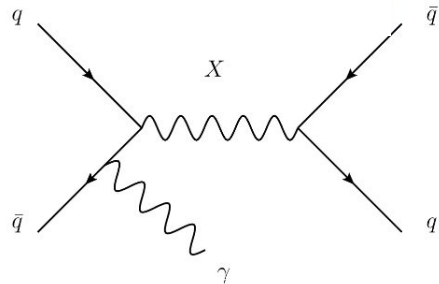
H. de la Torre, Northern Illinois University

Low mass resonance searches

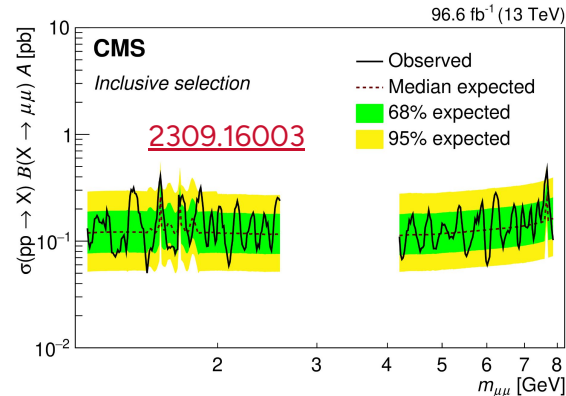
New techniques being implemented in recent years to cover corners of the phase space and final states that we don't have such a good handle in. Low mass for example requires special care due to trigger limitations.



CMS: Dimuon resonances using a dedicated dimuon stream with partial event information



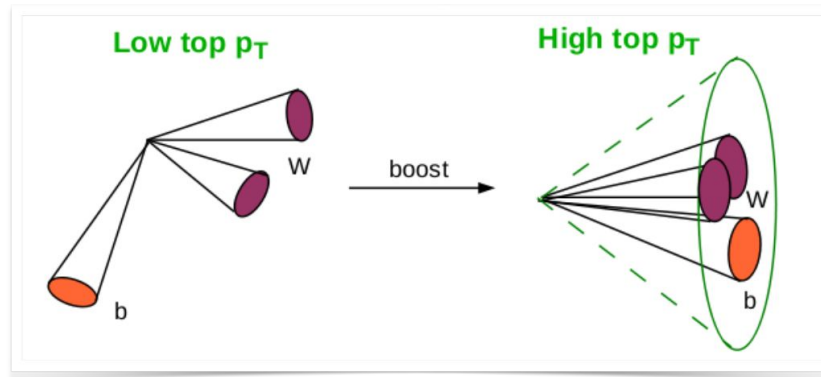
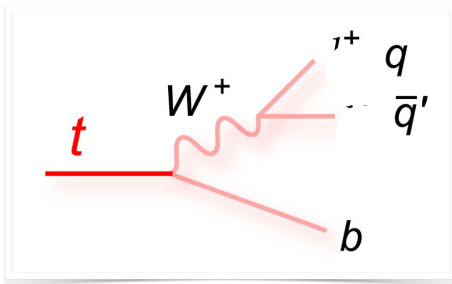
ATLAS: Low mass dijet resonance below jet trigger threshold by exploiting photon/jet initial state radiation



Jets and Jet tagging

Large-R jets are a useful tool for boosted scenarios

Same jet algorithms as standard jets (but larger size) are used to reconstruct complex hadronic structure, such as boosted hadronic top-quarks



Top-tagging

Series of techniques used to identify large-R jets coming from top-quarks

Substructure information

In ATLAS (Substructure based) [1808.07858](#)

Observable	Variable	Used for
Calibrated jet kinematics	p_T, m^{comb}	top, W
Energy correlation ratios	e_3, C_2, D_2	top, W
N -subjettiness	$\tau_1, \tau_2, \tau_{21}$	top, W
	τ_3, τ_{32}	top
Fox–Wolfram moment	R_2^{FW}	W
Splitting measures	z_{cut}	W
	$\sqrt{d_{12}}$	top, W
	$\sqrt{d_{23}}$	top
Planar flow	\mathcal{P}	W
Angularity	a_3	W
Aplanarity	A	W
KtDR	$KtDR$	W
Qw	Q_w	top

In CMS (Particle flow based)

[2004.08262](#)

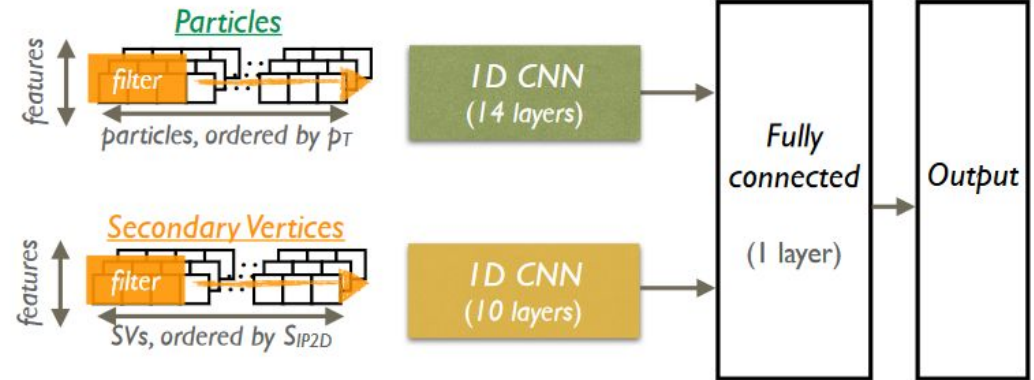
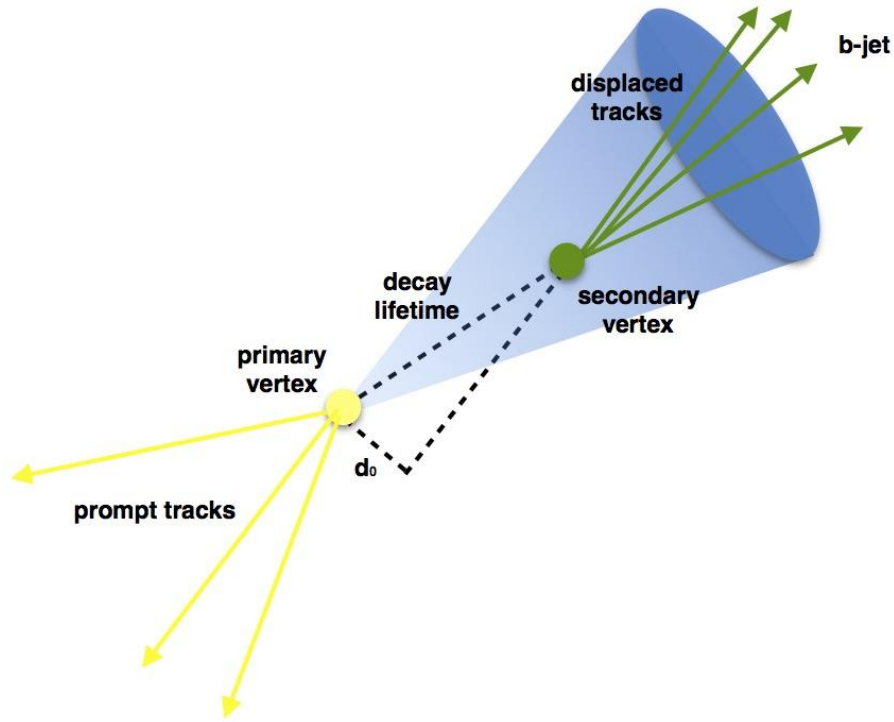


Figure 9. The network architecture of DeepAK8.

Flavor tagging



Both collaborations use different flavor of ML methods to identify jets originating from b-quarks using variables and objects related to displaced tracks and displaced vertices

CMS: [1712.07158](#)
ATLAS: [2211.16345](#)

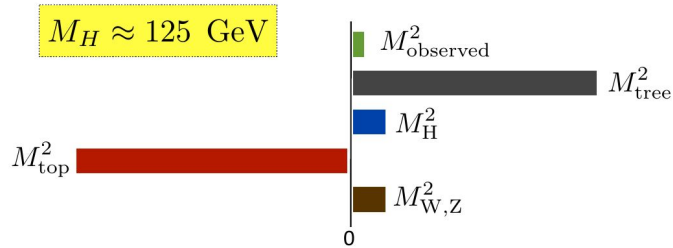
Higgs mass and fine tuning

$$\delta M^2 \propto \frac{a}{16\pi^2} g^2 \Lambda^2$$

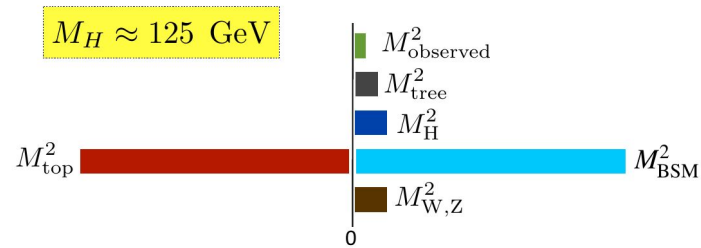
$$\Lambda_{\text{Planck}} \sim 10^{19} \text{ GeV}$$

$$M_H^2 = M_{\text{tree}}^2 + \left(\text{Higgs self-energy loop} \right) + \left(\text{Top quark loop} \right) + \left(\text{W, Z boson loop} \right)$$

$$M_H^2 = M_{\text{tree}}^2 + \left(\text{Higgs self-energy loop} \right) + \left(\text{Top quark loop} \right) + \left(\text{W, Z boson loop} \right) + \left(\text{BSM loop} \right)$$



Ultra-fine tuning!



Reasonable fine tuning!